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14. ABSTRACT This phase of a multi-year project continues and expands studies aimed at an improved biomechanical understanding of blast injury and development of new technologies for the mitigation of auditory injury from blast. Off-the-shelf fiber optic pressure sensors were used to measure and correlate external auditory canal (EAC) and intracranial pressure profiles in a cadaver head during blast generated by a shock tube. These wave forms were recorded and reproduced through a programmable bench top blast simulator system. This system, developed in Year 1, was improved through use of a folded horn approximating an exponential reduction in cross-section. The improved system delivers simulated blast wave forms with peak pressures exceeding 180dB SPL to human temporal bone specimens. Intracochlear pressures were measured using during harmonic and impulse stimuli using off-the-shelf fiber optic pressure probes with polyimides heating to resist damage from extreme pressures. Ossicular and round window membrane displacements were recorded simultaneously using a scanning LDV. These results give system compliance and group delay for the propagating blast wave, and the rate of energy transfer to the cochlea. Those parameters will be used to improve auditory hazard models and develop active systems protective against blast injury.					
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1 Extension and improvement of experimental setup

1.1 Specimen preparation

During the year, critical equipment and supplies were purchased. These include a small dedicated freezer and a set of human tissue specimens for temporal bone experiments. a larger freezer and an additional set of specimens are planned for the coming year. The freezer is locked and specimen handling will be according to existing protocols approved by the Office of Research Protections / Human Research Protection Office (ORP/HRPO). A Kopf stereotaxic micro-manipulator setup was purchased for surgical placement of the FISO pressure probes. The micro-manipulator arms were mounted on a base machined for the purpose by the UCSom machine shop (see Fig. 1).

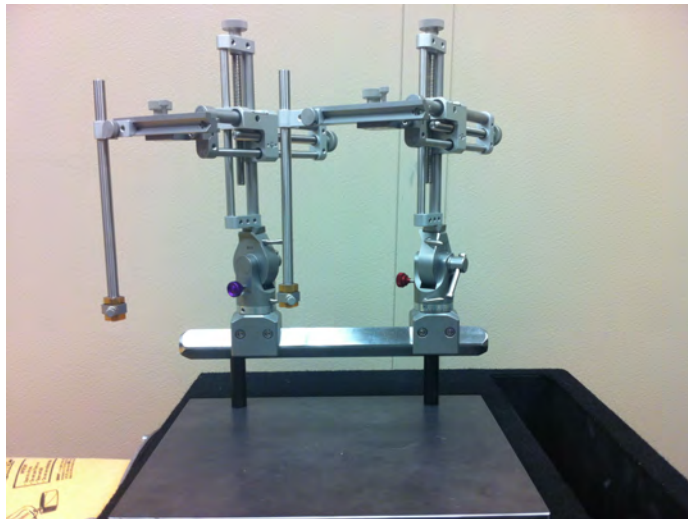


Figure 1: Kopf micro-manipulator setup

A supply of fluted and diamond burs suitable for the facial recess and cochleostomy procedures was acquired for the use of the project. Six 260 micrometer pressure sensors were acquired, of a new design incorporating a protective polyimide sheath over the active element and distal portion of the fiber. See Fig. 2

1.2 Polyimide-coated pressure sensors

FISO is the only commercial manufacturer of fiber optic sensors in the 260 μm diameter suitable for insertion into the SV and ST. For this reason, it is strongly desired that these fibers be made available in a more robust configuration. A new model of the FOP-M260 pressure sensor has now been introduced (Fig 2) in which the distal portion of the fiber near the active element has been sheathed in a polyimide coating, lending improved resistance to fracture. The diameter of the active fiber is increased only to 305 μm , still small enough for placement in the SV and ST. The polyimide-coated probes were used in the combined pressure - sLDV experiments discussed in a later section.

1.3 Improvement of the blast simulator:

1.3.1 High-pass filtering by the digital-to-analog converter

The sound card used for these experiments is a Hammerfall DSP Multiface II, a high-performance digital-to-analog interface widely used for multichannel sound recording. Inspection of the output waveform revealed a significant amount of high-pass filtering (low-frequency attenuation) at the interface output stage, the result of a capacitively coupled output (Fig 3).

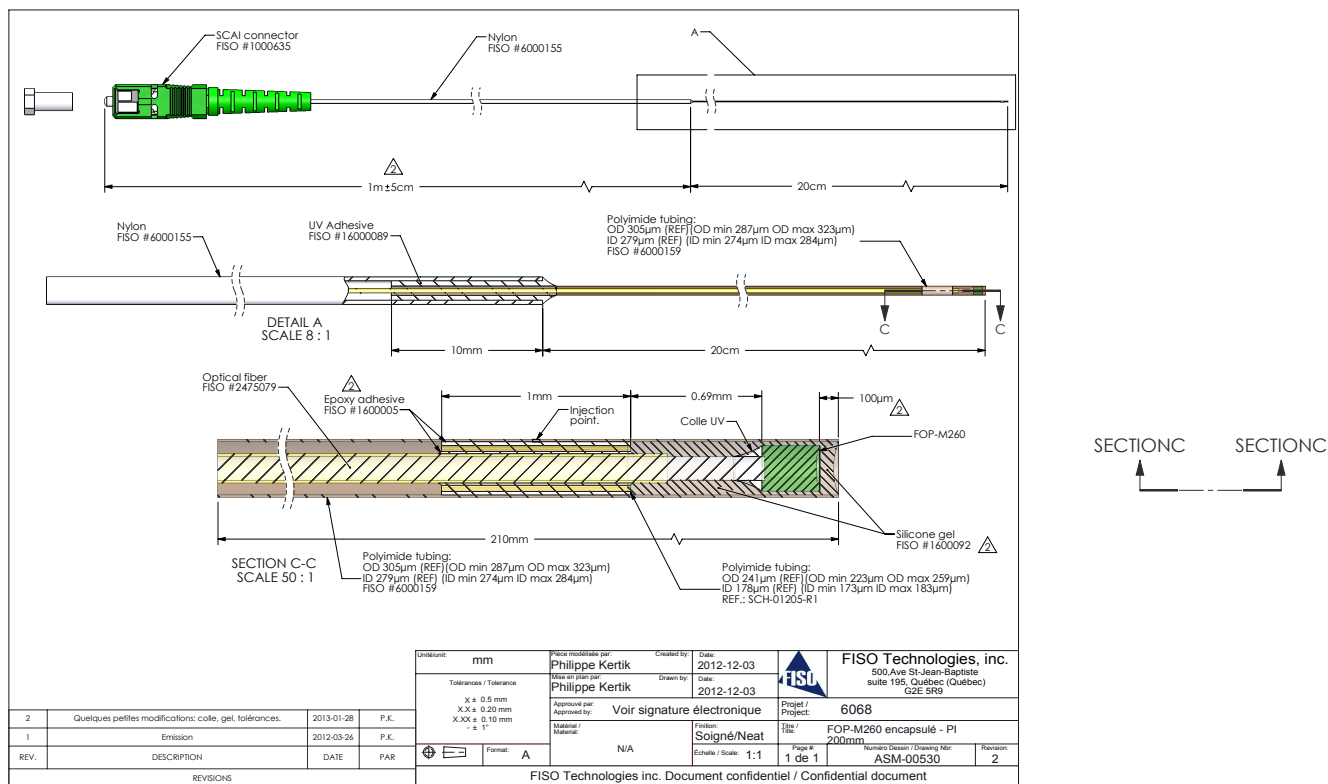


Figure 2: FISO pressure sensor with polyimide sheath

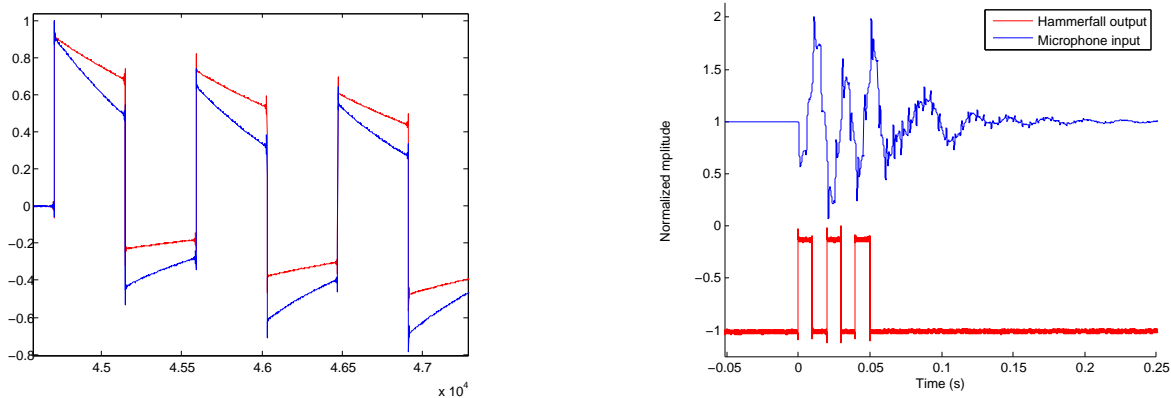


Figure 3: Hammerfall output with and without capacitive coupling (left). Output (right) without capacitive coupling, and microphone input (blue) at condensing cone

1.3.2 System response after output capacitor bypass

When the output capacitors were bypassed, a significant improvement in low-frequency response resulted. The analog output was tested and found to reproduce a 20-Hz square wave with good fidelity. Recordings of the condensed pressure response show a great deal of harmonic distortion and preferential amplification of higher frequencies (Figs. ?? and 4).

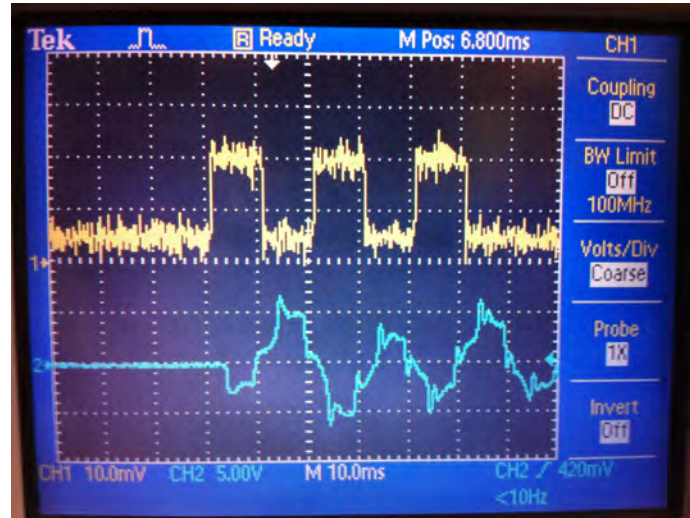


Figure 4: Hammerfall output (yellow) without capacitive coupling, and microphone input (blue) at condensing cone

1.3.3 Modification of the pressure condensation tract

In earlier testing, It has been observed that the blast simulator has constructed did reach desired sound intensities, but only at higher frequencies. This limited the ability of the simulator to re-create waveforms characteristic of blast as observed in the field. This limitation is the result of the simulator's short concentrating cone (Figure 5), the length of which is only a small fraction of the wavelengths of interest. The Friedlander type blast waveform recorded in actual explosive events in air, and physically simulated in shock tubes, concentrates a large amount of energy in lower frequency components, typically between 10 and 50 Hz. In order to concentrate energy at these longer durations, it is necessary to convert the velocity of the wave as generated into pressure over a tract length approximating one half wavelength of the lowest frequency of interest. For explosive waves in air, with a lowest high-energy component of 20 Hz, this corresponds with a tract length of 330 m/s divided by 40 Hz, or 8.25 m.

1.3.4 Pressure amplification by frequency

In previous testing, the pressure amplification of the simulator cone was found to be weighted toward the higher frequencies, with maximum near 2 kHz . The transfer function of the system was derived by measuring the sound level at the base using a pressure probe in a pipette (5, left) and at the tip of the horn in response to frequencies between 10 and 5000 Hz (Fig. 5, right). Note that pressure gain is no greater than 5 dB at frequencies up to 100 Hz. Greater pressure gain at lower frequencies is required to accurately simulates the extremely high, long-duration pressure waveform characteristic of blast.

1.3.5 Modifications to the blast simulator

Modifications to the concentrating cone were made following discussion with Brian Atkinson of UC Denver department of Electrical Engineering, a local speaker design expert. The modified horn was designed with a cross-sectional area that approximates an exponential/hyperbolic contour. The horn was mostly constructed

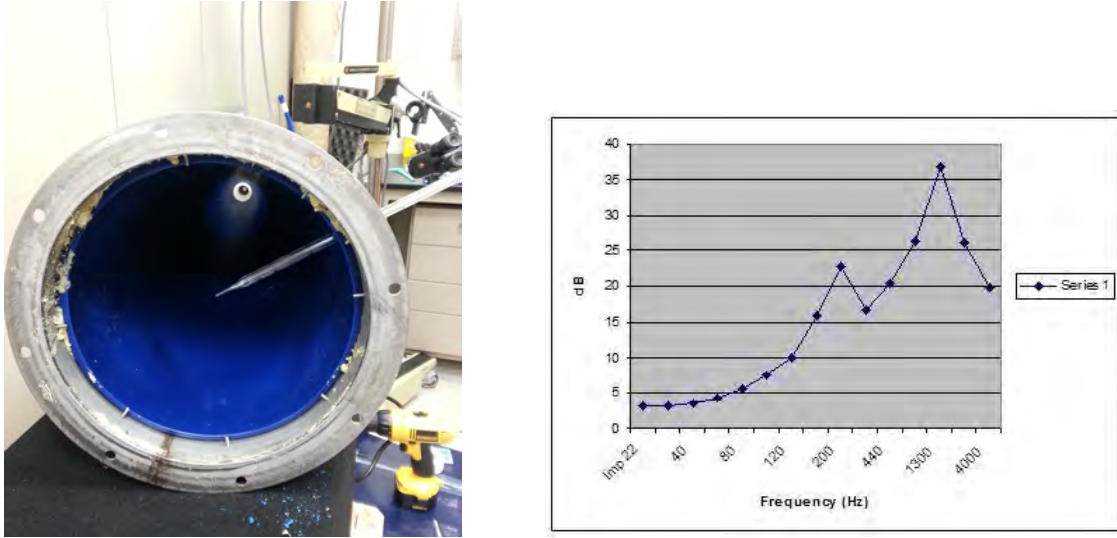


Figure 5: The blast simulator with condensing cone (left), and pressure gain by frequency, showing lower performance at low frequencies.

from solid core PVC tubing of various diameters that were connected with reducing couplings, and folded into a manageable size with 90° elbows. The final turns of the horn were similarly constructed from $\frac{1}{2}$ " copper pipe, and terminate on a section of flexible $\frac{1}{4}$ " copper pipe that is bent into an appropriate position for delivery to the specimen. The overall length of the modified concentrating horn is in excess of 11 m, thus the expected corner frequency of the resulting high-pass filter is approximately 15 Hz. The transfer function of the system was derived by measuring the sound level at the base and at the tip of the horn in response to frequencies between 10 and 1000 Hz (Fig. 6, right). As predicted, the gain produced by the modified horn (blue) is relatively flat at ~ 25 dB above 15 Hz, and rapidly drops to below 10 dB at lower frequencies. Compared to the short concentrating cone (black), gain is substantially increased at low frequencies (between 20 and 200 Hz).

The effect of the improved horn was to dramatically boost pressures at lower frequencies, enabling the sLDV experiments to be conducted using peak pressures characteristic of near-field blast exposure.

1.4 Reproduction of shock tube (simulated blast) waveform

In studies of blast effects, it is common practice to use a shock tube to re-create the gas dynamics seen in actual explosive events. Shock tubes have been built across a broad range of dimensions and operating parameters, and have been used to study a variety of phenomena. All have in common that a pressurized chamber is suddenly vented into a length of tubing when a diaphragm separating the two is breached, either by puncture, or simply at the strength of the diaphragm. The blast waveform simulated here was reported during experiments in January 2013 using a mobile 12 inch shock tube built and operated by Applied Research Associates (Littleton, Colorado) and performed at the University of Colorado school of medicine. The waveform recorded exhibits the qualities common to the Friedlander type waveform characteristic of blast events: a sharp leading edge marks the passage of the shock wave with its high-pressure zone immediately following; the high-pressure portion of the waveform quickly decays and is followed by a longer under-pressure phase and subsidence to ambient pressure (Figure 7).

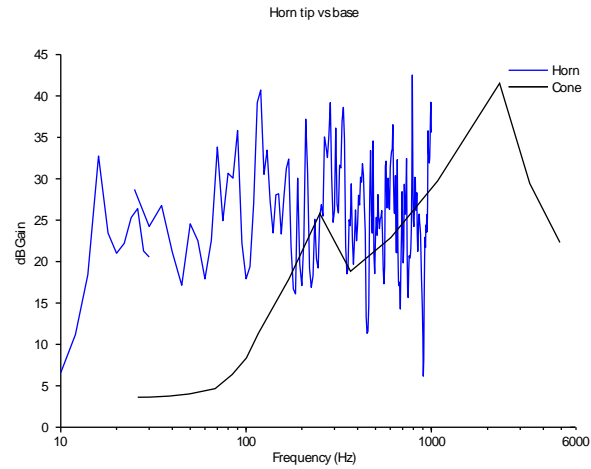


Figure 6: The blast simulator as improved with folded exponential tract (left), and pressure gain by frequency, showing improved performance at low frequencies.

2 Scientific Progress during the Report Year

2.1 Correlation of intracranial and ear canal pressures during blast events

The research team collaborated in January 2013 with groups from Applied Research Associates and the University of Virginia in an investigation of blast-induced TBI. The focus of the study was a possible injury mechanism from cavitation in the cerebrospinal fluid (CSF).

2.1.1 Methods

A human cadaver head was instrumented with strain gauges and pressure probes at multiple locations in order to map the pressure field and deformation resulting from shock wave propagation through the skull. Additionally, pressure probes were inserted into the ear canals through cannulae with the active element placed approximately 1 mm from the TM. The specimen was then filled with degassed DI water as a CSF simulant and subjected to simulated blast events at rupture pressures exceeding 150 psi. The specimen with instrumentation was draped and mounted with the calvarium downward to retain liquid and mounted approximately 50 cm from the shock tube (Fig. figure 8).

2.1.2 Results

Ambient pressure Blast overpressure was measured by an electromechanical pressure probe at a distance of approximately 30 cm from the specimen. The initial peak was typically of 20 to 25 psi in magnitude, with ringing at a 25 msec period caused by reflections (Fig 9).

Intracranial pressure Pressure was measured within the skull at several locations. Intracranial pressure at the instrumented location nearest the right EAC reached an initial peak of 14 psi, then was quickly damped to levels of 1 - 2 psi, following the ringing of the ambient field (Fig 10).

EAC pressure Pressure was measured within the right EAC at approximately 1mm from the TM. Pressure reached an initial peak exceeding 10 psi; this peak was clipped. Scaling of the measured waveform to the

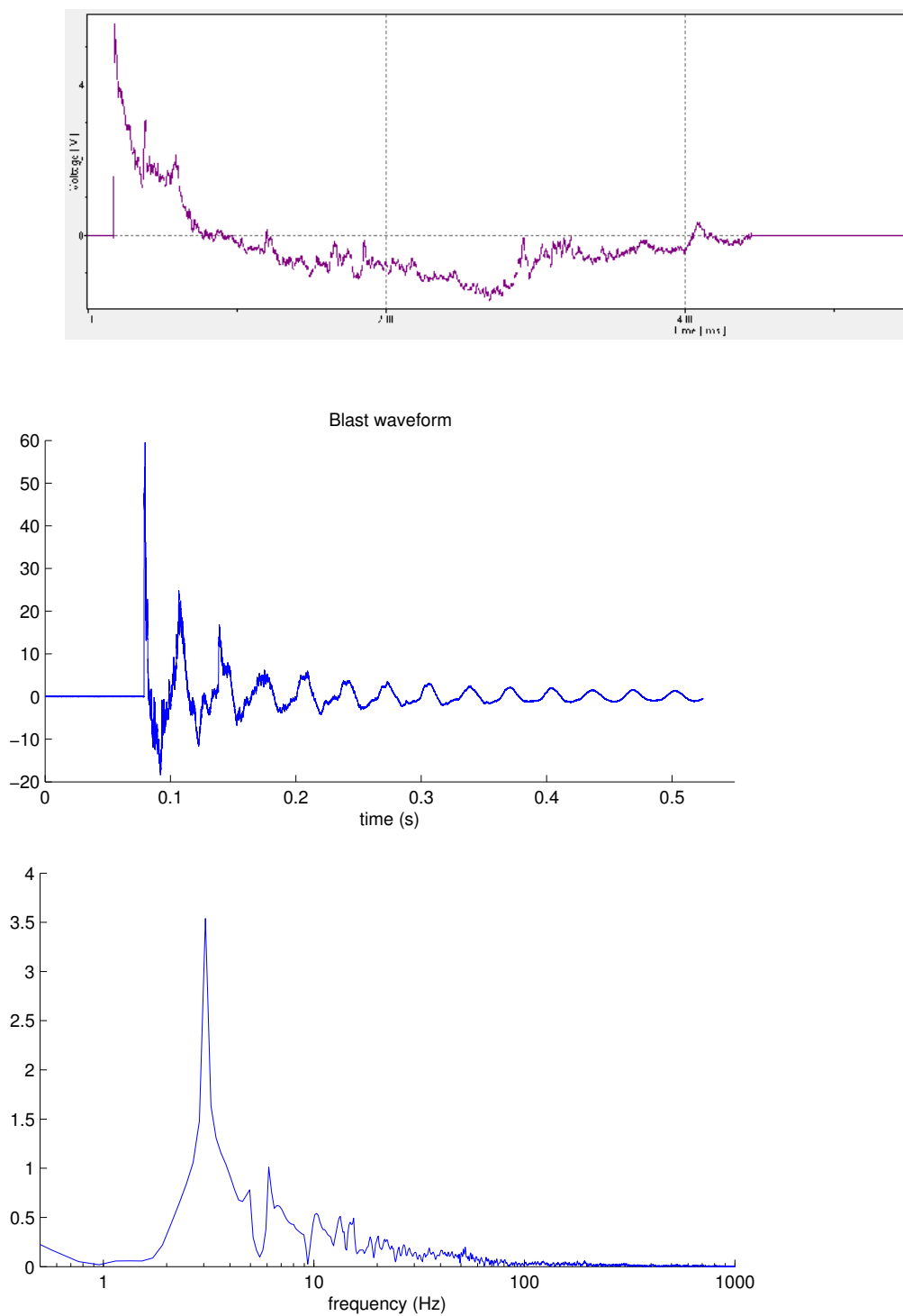


Figure 7: Blast waveform (top), extended series (center) and energy spectrum (bottom) as recorded from ARA 12" shock tube

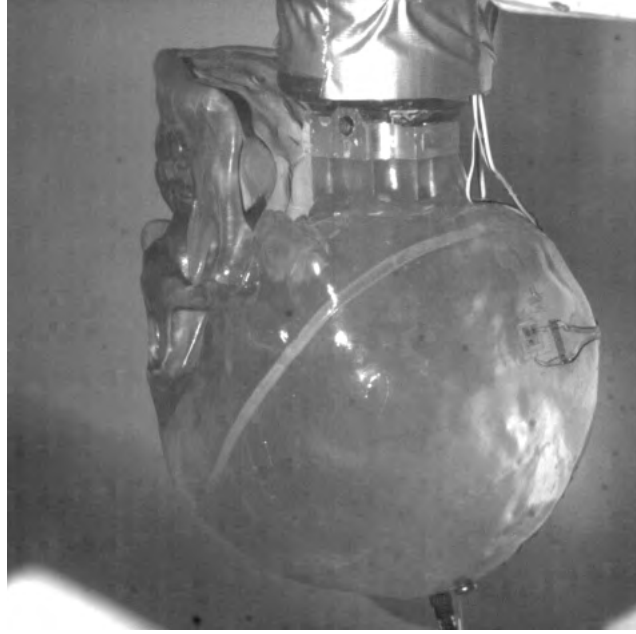


Figure 8: Instrumented specimen for intracranial and EAC pressure measurement

ambient and intracranial pressures indicates that EAC pressures were equal to or slightly higher than ambient levels, and exceed intracranial pressures by a factor of approximately 8. (Fig 11).

2.1.3 Discussion

Waveforms recorded in multiple locations throughout the specimen create a detailed map of the blast wave's progression. Of particular interest are the shaping of the impinging wave by the ear canal, and the magnitude and phase relationships between the EAC and intracranial pressures. These will be used to establish an approximate relationship between peak pressures causing peripheral auditory injury and intracranial pressure fields causing TBI through mechanisms including cavitation and diffuse axonal shear. The results obtained from this study shed light on the dynamics of wave propagation through the auditory system, and will be very useful to the design of future experiments. Several improvements to the experimental setup were suggested. Use of multiple probes spanning a larger dynamic range of pressure will permit capture of the initial peak while retaining the resolution necessary for study of the middle ear and intracochlear pressures. Protection of the probes from the blast wind is key to preventing sensor damage. In this study, several probes failed at or near the termination of the rigid cannulae, suggesting that a tube with uniform compliance extending outside the wind-affected zone is needed. The fibers themselves are prone to failure near the active element at the tip. FISO has recognized this problem and introduced a more robust design (see below).

2.2 Intracochlear pressure measurement

An experimental method for measurement of cochlear pressures using off-the-shelf sensors and circuitry has been developed and demonstrated. This report continues the investigation into measurement techniques described in the previous Annual Report.

Commercially available, off-the-shelf pressure sensors have now been used to measure differential intracochlear pressures simultaneously with LDV measurements of ossicular velocity. The use of readily available commercial sensors with a very large dynamic range opens the possibility for measurements and characterization of ossicular dynamics across the sound pressures characteristic of normal hearing and the extreme pressure levels seen in blast events. These experiments also act as proof of concept for application of 260 micrometer diameter sensors for direct intracochlear pressure measurements, simultaneously with LDV measurement of ossicular velocity, without the need for separate input pressure intensity levels.

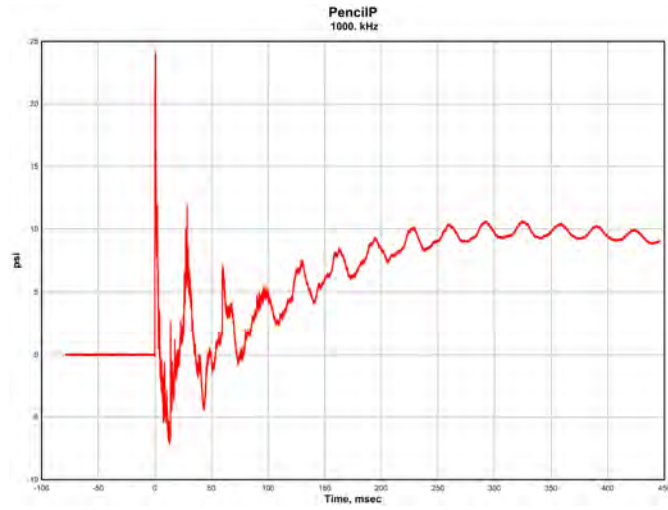


Figure 9: Ambient pressure during shock tube blast simulation

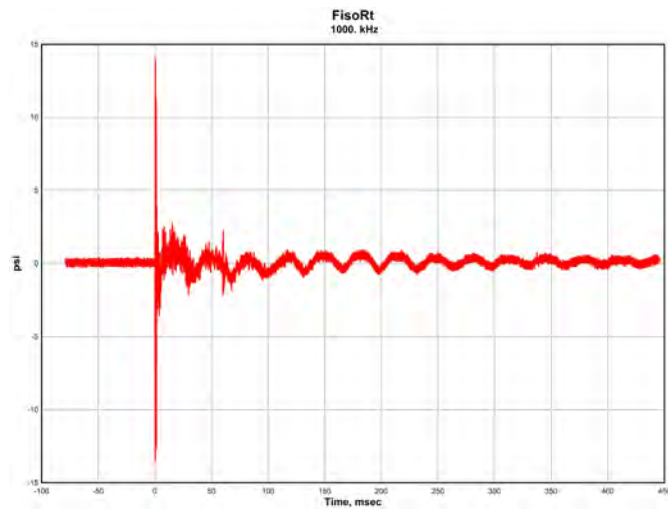


Figure 10: Intracranial pressure during shock tube blast simulation

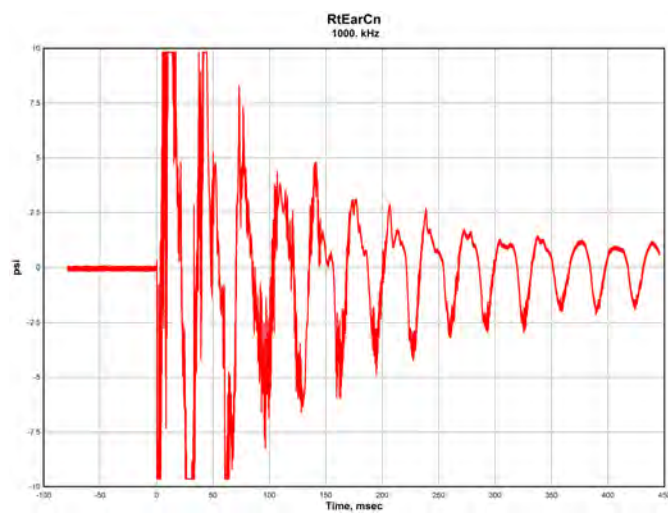


Figure 11: Ear canal pressure during shock tube blast simulation

2.2.1 Experiments with newly acquired specimens

Tests of stapedial velocity and intracochlear pressure were performed to confirm that the newly acquired temporal bones were ASTM-compliant, that is, that the stapedial velocity response to acoustic stimuli for these specimens is within the band considered typical in ASTM-F2504. A right temporal bone was selected, and found to be within the typical band of response at frequencies up to 4 kHz (Fig 12). Intracochlear pressure magnitude and phase for the scala tympani (ST) in this specimen were typical (Fig 13); however, the probe measuring pressure in the scala vestibuli (SV) failed during placement. Multiple failures of the 260-micron probes have underlined the problem of sensor fragility. A recent design improvement in the fiber optic probes will reduce the frequency of sensor failure (Fig. 2).

2.3 Correlation of ossicular motion and intracochlear pressures

The team contracted in July 2013 with a team from Polytec, Inc. in an investigation of ossicular motion using a scanning laser doppler vibrometer (sLDV) and intracochlear pressure measurements using FISO fiber-optic pressure probes, during high-intensity acoustic stimulation.

2.3.1 Surgical preparation

Three human cadaver hemi-heads (from two individuals) were prepared for measurements of ossicular dynamics and intracochlear pressure measurements by Dr. Herman Jenkins of the University of Colorado School of Medicine Department of Otolaryngology. Visualization of the ossicles, and access to the cochlea, were provided via an extended facial recess (Fig. 14), which retains normal physiological function. In one specimen, cochleostomies were performed to provide access to the scala vestibuli and scala tympani (fibers visible on the left in Fig. 15).

2.3.2 Methodology: Specimen preparation

Specimens were wrapped in an absorbent waterproof pad to minimize potential contamination and maintain donor dignity. The specimens were affixed to an adjustable plate mounted on a goniometer attached to the machined micromanipulator base, and aligned in front of the sLDV head on a rotatable post (Fig. 15). Glass fiber pressure probes were secured to the micromanipulator arms, which were also mounted to the micromanipulator base. Sound was delivered to the ear canal using a short section of Tygon tubing attached to the flexible copper section of the modified blast simulator concentrating horn. A microphone probe tube and a FISO pressure probe were inserted through the tubing in order to monitor stimulus delivery.

2.3.3 Methodology: Visualization with sLDV

The sLDV was oriented and focused into the middle ear, and several measurement points defined on points of interest (Fig. 16) which were then joined together as a single object for visualization and off-line analysis. When possible the following structures were characterized (from upper left to lower right): head of the malleus, body of the incus, buttress over the incus (fixed bone for reference), long process of the incus, capitulum of the stapes, anterior and posterior crus of the stapes, footplate of the stapes, stapedial tendon, and round window. The pressure probes in the scala vestibuli (left) and scala tympani (right) are also visible in Figure 15. Signals sent to the blast simulator were generated by the sLDV system (pure tones), or by a Tucker Davis Technologies (TDT) digital to analog converter (impulses/burst waveforms), were attenuated to the desired sound level using a TDT attenuator, and recorded by the sLDV system.

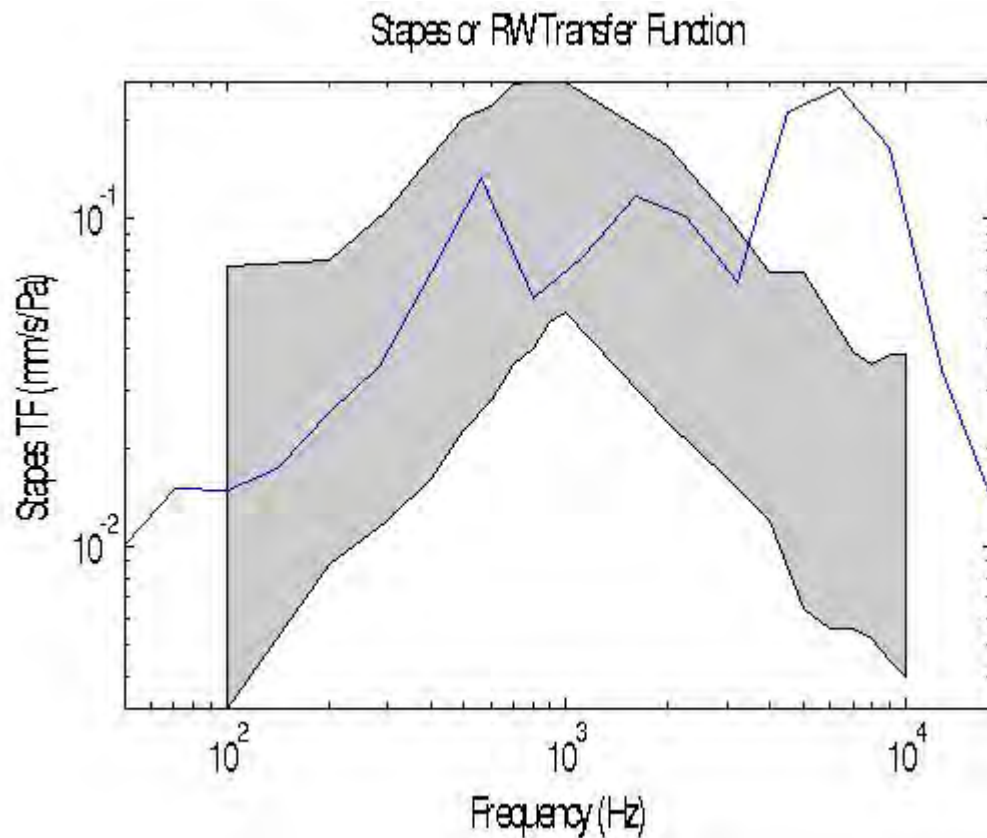


Figure 12: Stapes velocities in right temporal bone, 130222

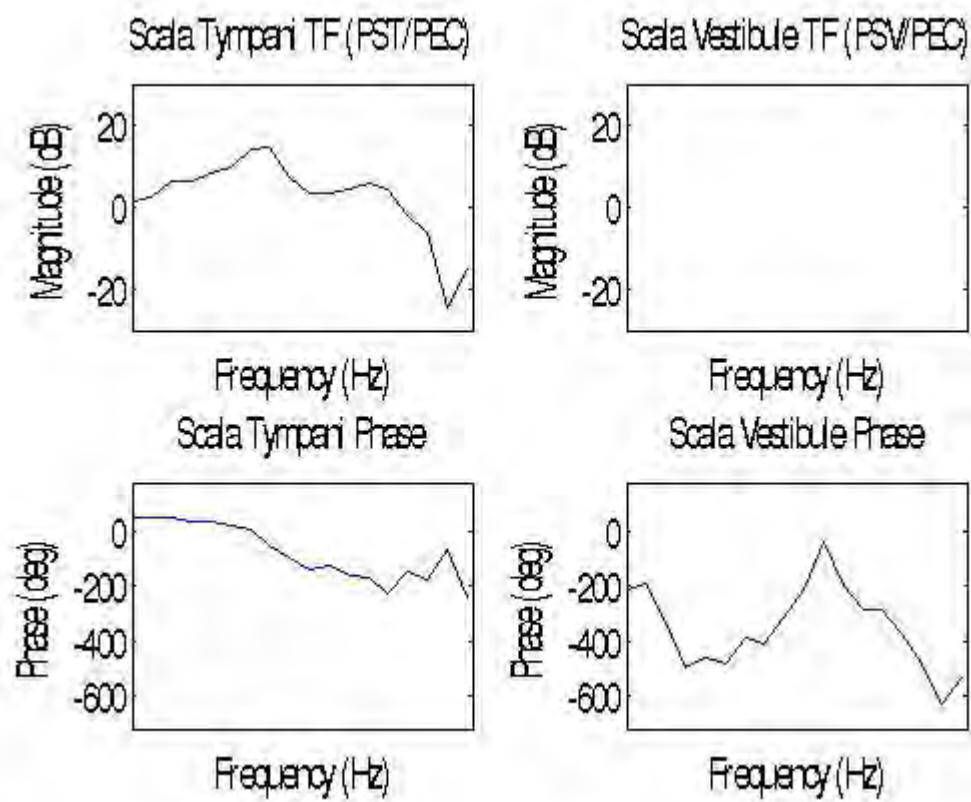


Figure 13: Intracochlear pressure in right temporal bone, 130222

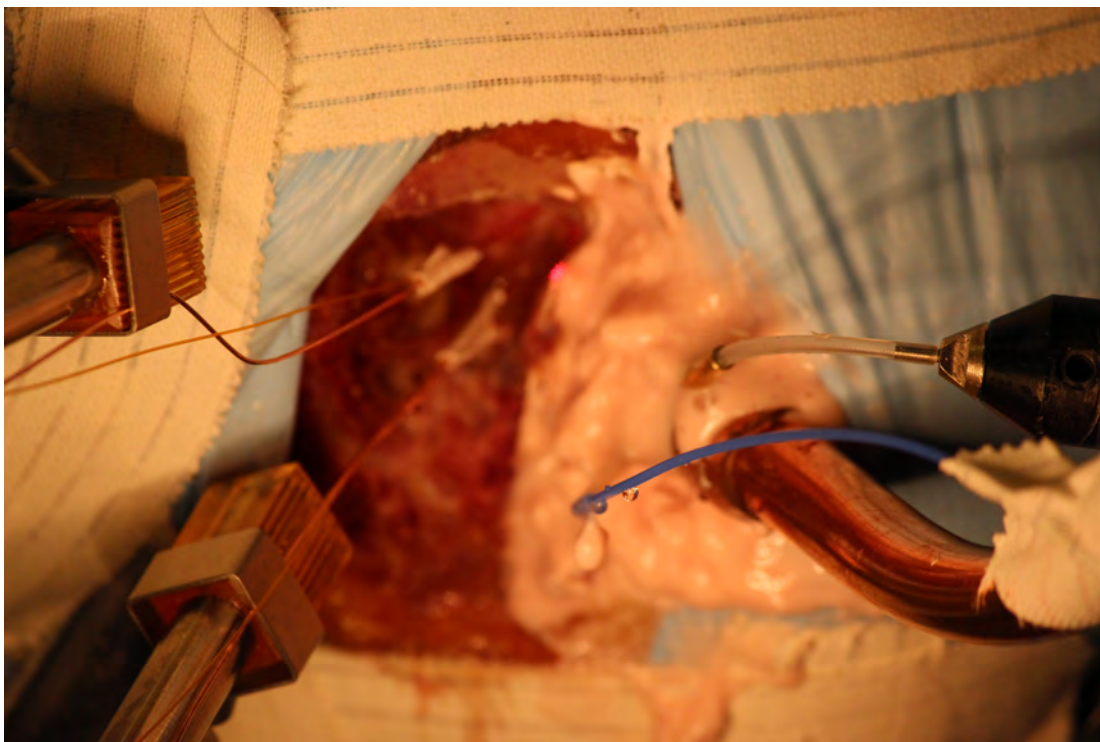


Figure 14: Surgical preparation, showing placement of pressure probes

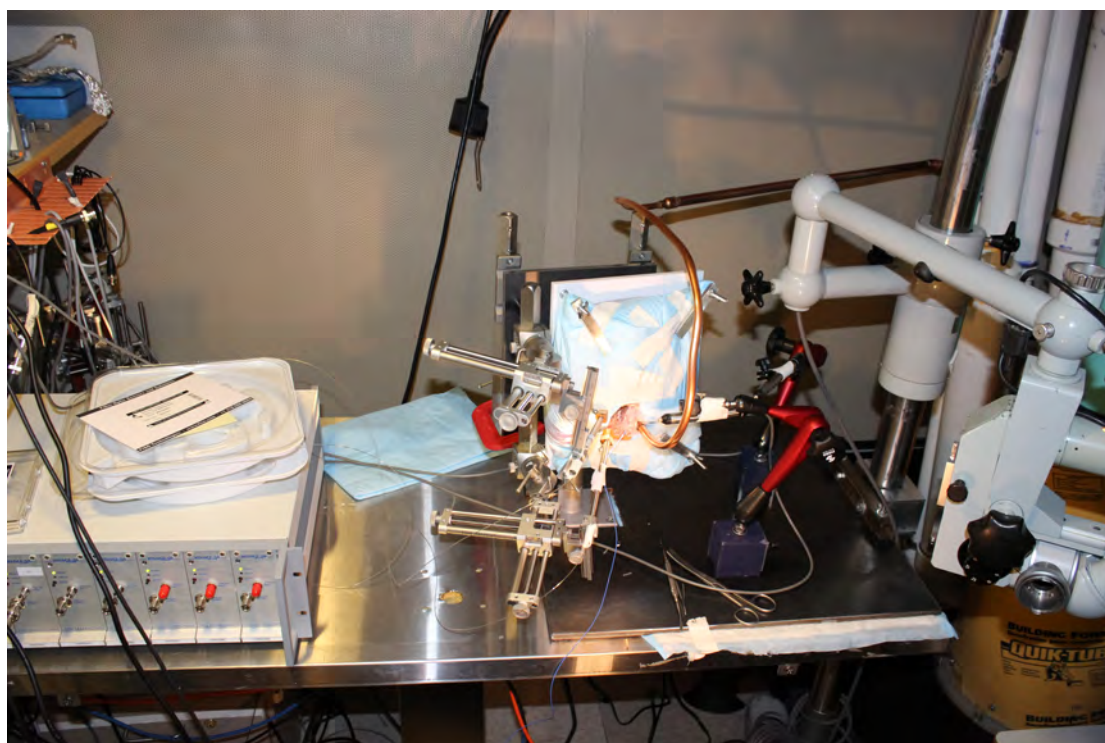


Figure 15: Specimen placement, with micromanipulators and pressure measurement front-end

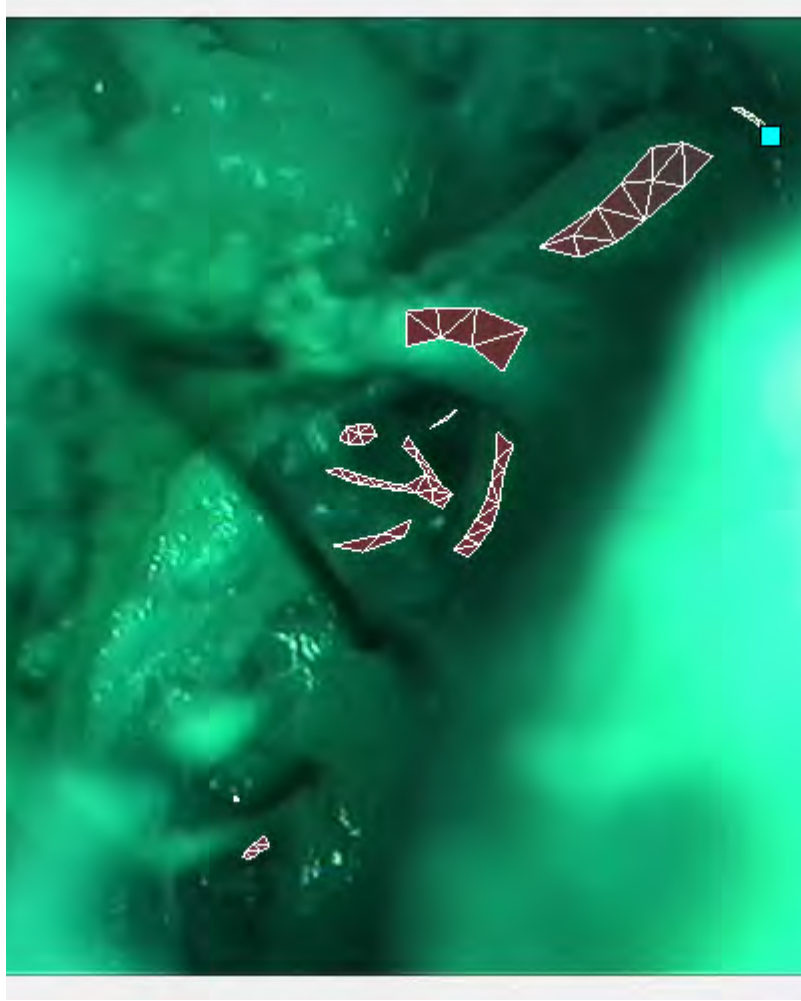


Figure 16: Meshed points of interest throughout ossicular chain and round window

2.3.4 Background: Method of Measurement

A pattern of points was defined for each element of interest, from the malleus head to the round window membrane. These were associated into a mesh for each element, and analyzed as a rigid body system. The sLDV measured the velocity in the Z dimension (in and out of the page) for each point of interest, for each stimulus in turn, then recombined to generate a synchronized output. The blast/impulse waveform sent to the blast simulator, and a short section at the start of the response are shown in Figure 7. The meshed areas of interest, from the malleus head to the round window membrane, are shown in Figure 16. Examples of velocity waveforms from several points along the ossicular chain in response to selected waveforms are shown

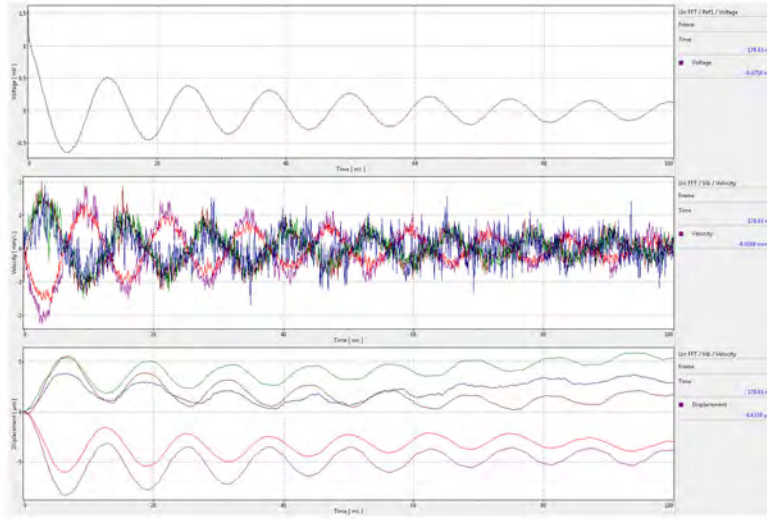


Figure 17: Ossicular velocities under harmonic stimulation: 80 Hz, 114 dB SPL, specimen 173L: Malleus head (Purple), Incus body (Red), Incus long-process (Green), Stapes capitulum (Dark Red), Stapes footplate (Navy Blue)

in the following figures. Velocities were integrated to yield displacement, which are also shown. The pressures within the two scalae are shown in the lowermost plots. Qualitatively, the amplitudes and latencies of the responses are consistent with our expectations. The largest velocities (and displacements) were measured on the head of the malleus and adjacent body of the incus, and the smallest magnitudes were measured in the stapes. The long-process of the incus and the stapes moved in opposite phase to the malleus, and the round window moved in opposite phase to the stapes. Displacements in response to the impulse/blast waveform were up to approximately 20 ms in duration, with quick transitions from positive to negative. Pressure measurements in the scala showed phase and magnitude relationships to the stimulation and to one another consistent with published results[1]. Quantitative assessments of the measured responses are in process, and will be used to fit parameters to an auditory hazard model.

2.3.5 Reconstruction

The sLDV system also combines the responses of individual points into objects, which it then represents via changes in color and by rendering motion in three dimensions. Visualization in this manner allows a quick assessment of data magnitude and quality (e.g. identifying improperly assigned points). In particular, the phase inversion between the malleus/incus body and the incus long-process/stapes that is suggestive of a lever/see-saw motion of the incus, as well as the phase inversion of stapes and round window due to fluid displacement within the cochlea, are very clear in the video.

2.3.6 Ossicular Velocity under Harmonic Stimulation at Moderate Intensity

Figure 17 illustrates the phase differences among the elements of the ossicular chain under conditions typical of normal hearing. The malleus head and incus body are seen to move roughly in antiphase with respect to the incus long process and stapes, reflecting the pivoting behavior of the incus. The phase lag between ossicles is evident, and will be used to estimate the dynamic parameters of the ossicular joints. Not shown

here but present in other data sets is the round window membrane velocity; as expected, it is nearly antiphase to the stapes.

2.3.7 Ossicular Velocity under Harmonic Stimulation at High Intensity

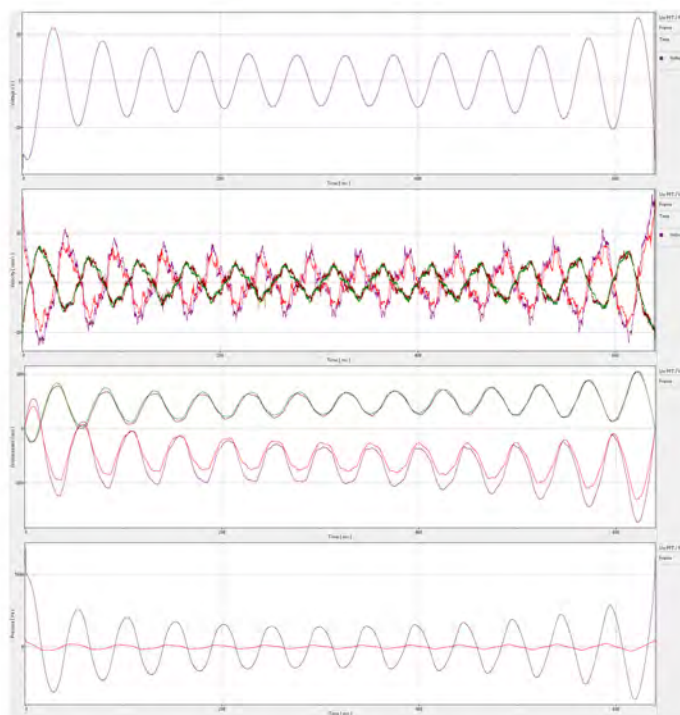


Figure 18: Harmonic stimulus response, specimen 85R, 20 Hz, 160 dB SPL. Malleus head (Purple), Incus body (Red), Incus long-process (Green), Stapes capitulum (Dark Red) Pressure: Scala vestibuli (purple), Scala tympani (red)

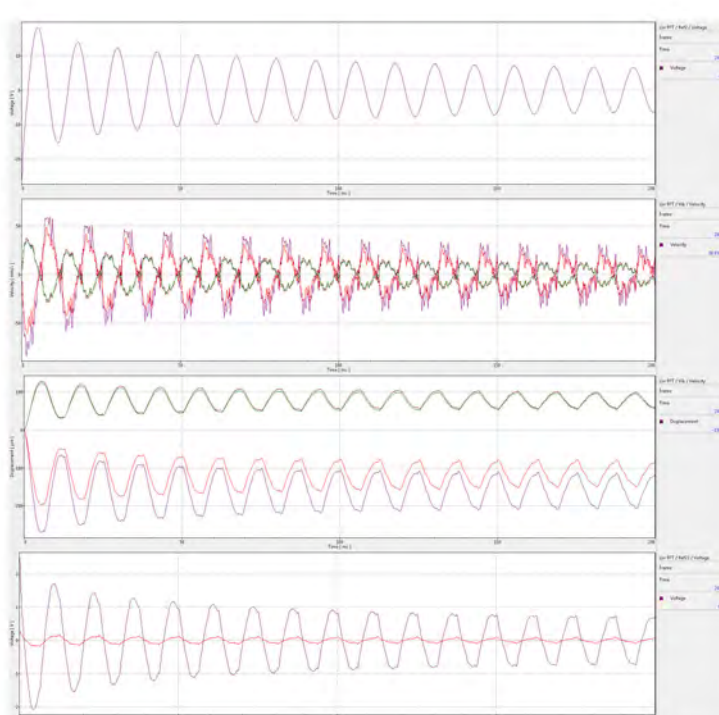


Figure 19: Harmonic stimulus response, specimen 85R, 80 Hz, 160 dB SPL. Malleus head (Purple), Incus body (Red), Incus long-process (Green), Stapes capitulum (Dark Red) Pressure: Scala vestibuli (purple), Scala tympani (red)

Ossicular response and intracochlear pressures display some nonlinear behavior as sound pressures exceed 140 dB SPL. Visible distortion in the response waveform is seen at 160 dB SPL, as shown in Figures 18 and 19.

2.3.8 Ossicular Velocities and Intracochlear Pressures under Impulse Stimulation

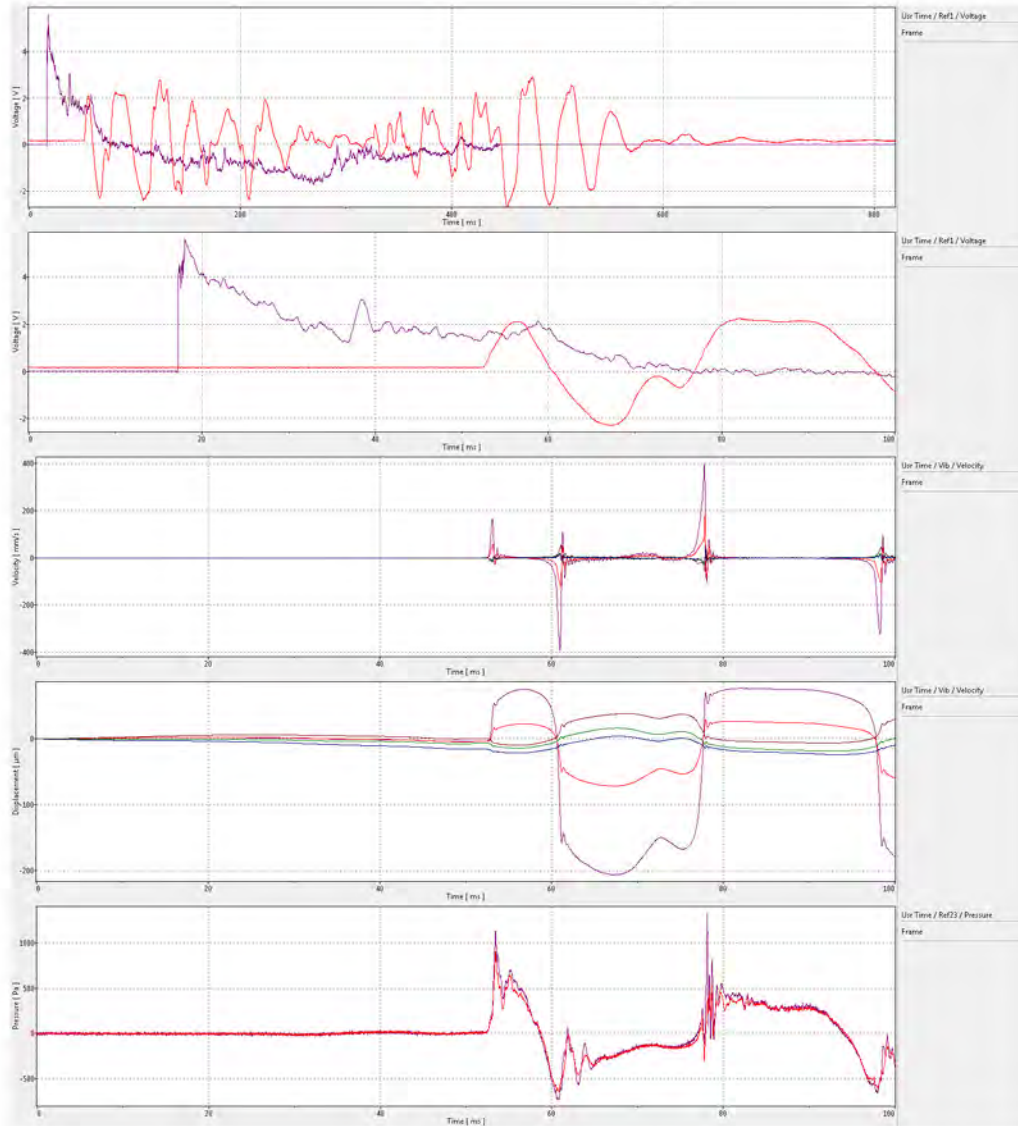


Figure 20: Ossicular velocities and intracochlear pressures, specimen 85R: Malleus head (Purple), Incus body (Red), Incus long-process (Green), Stapes capitulum (Dark Red) Pressures: Scala tympani (purple), Scala vestibuli (red)

Data sets including both velocity and pressure will be useful in modeling the transfer of energy, with the potential for both stimulation and injury, as an impulse propagates through the auditory system. Figure 20 shows the relationship among the ossicular velocities and intracochlear pressures during an impulse event. In the lower two plots, note the ratio of magnitudes between malleus and stapes displacement; this is the transformer ratio of the middle ear. The phase delay between tympanic membrane and stapes footplate is the middle ear group delay, typically about 83 microseconds. The much smaller cochlear group delay is seen in the lowermost plot as the phase delay between scala vestibuli and scala tympani.

2.3.9 Ossicular Velocities under Intense, Brief Impulse

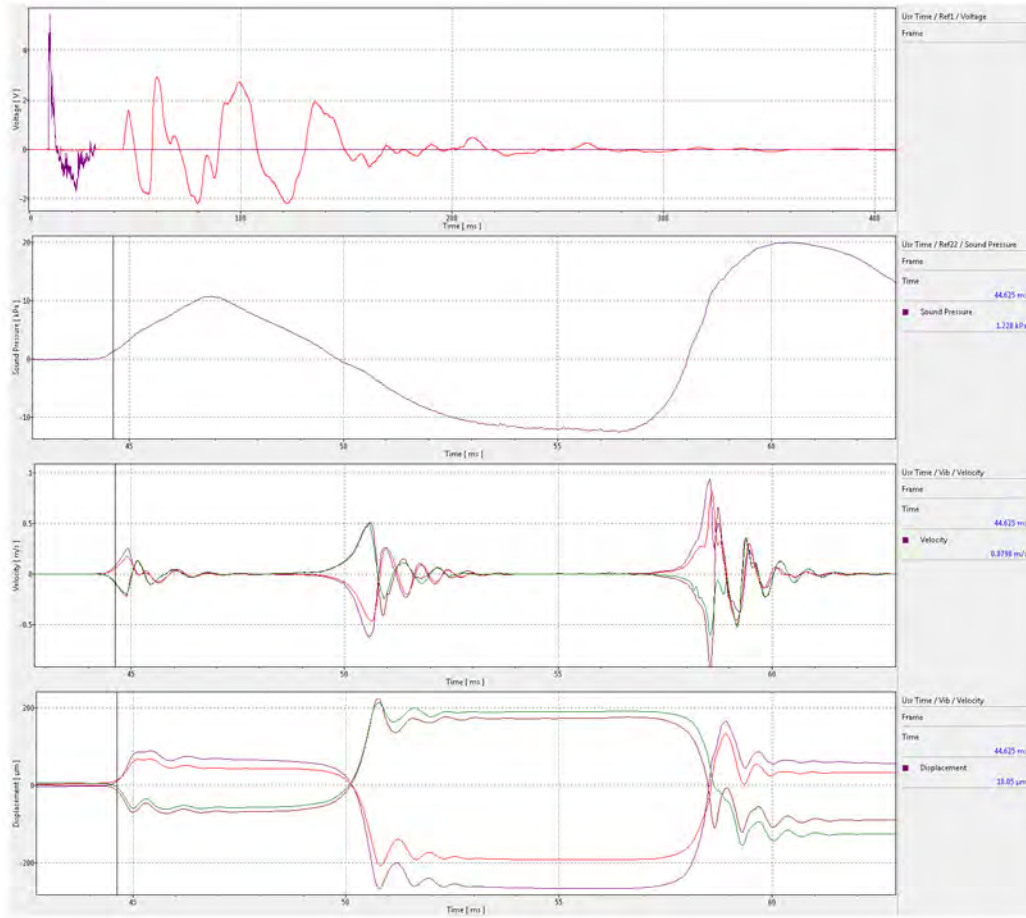


Figure 21: Ossicular velocities and intracochlear pressures, specimen 173L: Malleus head (Purple), Incus body (Red), Incus long-process (Green), Stapes capitulum (Dark Red), Stapes footplate (Navy Blue) -no pressure measured

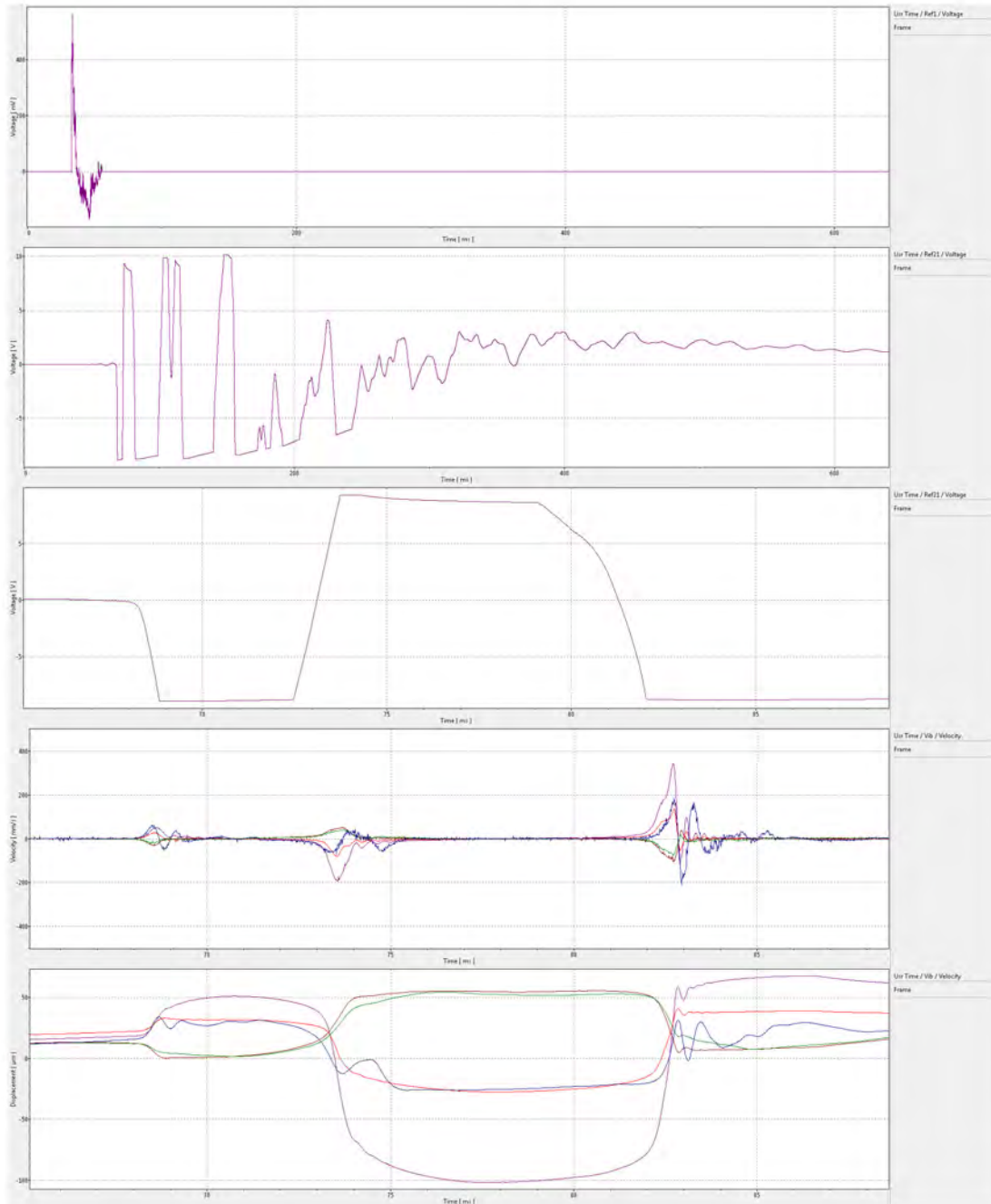


Figure 22: Ossicular velocities, specimen 85L: measured: Malleus head(Purple), Incus body (Red), Stapes capitulum (Green), Stapes footplate (Dark Red), round window (Navy Blue)

A key objective of this research is to assess the behavior of the auditory system under extreme conditions, and to estimate its dynamic parameters under those conditions. Figures 21 and 22 show how these measurements will be useful for that purpose. The displacement (lowermost plot) and velocity (second from bottom) of the ossicles define a nonlinear and rate-dependent suspensory system serving to limit the ear's response to impulse and loud noise.

2.4 Discussion:

Modifications to the blast simulator pressure condensation tract have greatly improved our ability to deliver high-amplitude, low-frequency acoustic stimuli simulating blast events. A number of further improvements are in process:

- The amplifier will be relocated outside of the speaker box and sound chamber for improved isolation and cooling.
- The conical base of the concentrating horn and flexible rubber coupling will be replaced with larger PVC sections.
- The cross-sectional area of the horn will be reduced smoothly, and the progression function optimized for the frequencies of interest.

The initial posterior tympanotomy and thinning of the scalae are now performed by a highly experienced otologic surgeon (Jenkins), who leaves the locations of the cochleostomies as dished, blue-lined areas of the scala vestibuli and scala tympani. The final puncturing of the scalae is performed by a post-doctoral researcher (Greene), under saline, just before measurements begin. This allows specimens to be prepared in advance, while reducing the likelihood of damage to the labyrinth and loss of cochlear fluid during handling.

The improvements to specimen setup, and the pressure probe design appear to have substantially improved durability of the pressure probes. The dedicated micromanipulators, that are firmly mounted to the specimen base plate, provide a stable base from which the probes can be placed. Mounting all components on a single base allows manipulation as a single unit, rather than attempting to manipulate each component individually. This configuration is suited both to experiments with the single-axis LDV, in which the specimen is mounted horizontally for stability, and with the sLDV, in which the specimen is mounted vertically to afford a wide field of view.

2.5 Acknowledgments:

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